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SPATIAL FILTERS FOR OPTICAL CORRELATION

University of Dayton Research Institute

David L. Flannery

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APPROVED:

PETER D. GIANINO
Project Engineer

FOR THE COMMANDER:

HAROLD ROTH, Director
Solid State Sciences
Electromagnetics & Reliability Directorate

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David L. Flannery

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University of Dayton Research Institute
Dayton OH 45469

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13. ABSTRACT (Maximum 200 words)
A set of images comprising an aximuthal training set of M-48 tank images was used as the basis of simulation studies to assess the performance of improved metric sort ternary phase-amplitude filters using gray scale inputs. Results compared favorably with those obtained with other filter formulations. Binary versions of these images were used as the basis for a study of image binarization effects on optical correlation performance. The study indicated excellent correlation performance with binarized inputs and references. A set of T-72 tank images, including an azimuthal training set and input scenes with clutter, was the basis for a simulation study comparing correlation performance of smart TPAFs with gray scale and binary input scenes. The correlation results with binary images were at least equal in quality to those using gray scale inputs. 128x128 correlation filters were generated on a zero-filled 256x256-pixel array. These filters were correlated with 128x128-pixel input scenes (imbedded in a zero-filled 256x256 array for digital simulations). Methods for implementing these filters in a correlator with 128x128-pixel SLM's at both input and filter planes were investigated by both simulation and experimentation. The two methods provided acceptable results.

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1.0 INTRODUCTION

This is the final technical report for Task S-1-7619 of the Air Force Rome Laboratory's Expert Science and Engineering Program, Contract F30602-88-D-0028, administered by the University of Dayton. The task investigated filters for optical correlation and was carried out by the Applied Physics Division of the University of Dayton Research Institute over the period from May 1991 to May 1992. The principal investigator was Dr. David L. Flannery. Imagery furnished by Dr. Dennis Goldstein of the Air Force Wright Laboratory, WL/MNGS, Eglin AFB, Florida was the primary subject of the investigations and hereafter is refered to as "government-furnished" imagery. The experimental magneto-optic correlator used for filter verification is comprised largely of equipment on loan from Martin Marietta Corporation, Denver, Colorado.

Following is a synopsis of task elements addressed in the effort and their results:

1.1 A first set of government-furnished images comprising an azimuthal training set of M-48 tank images was used as the basis of simulation studies to assess the performance of improved metric sort (IMS) TPAF (ternary phase-amplitude filter) filters using gray scale inputs. Results that compared favorably with those obtained with other filter formulations were obtained.

1.2 Binary versions of the M-48 training set images were used as the basis for a study of image binarization effects on optical correlation performance. This portion of the effort was jointly supported by Martin Marietta and resulted in a stand-alone technical report which is incorporated in this report as Attachment A. The study indicated excellent correlation performance with binarized inputs and references.

1.3 A second set of government-furnished images with a T-72 tank as the subject, including an azimuthal training set and input scenes with clutter, was the basis for a simulation study comparing correlation performance of smart TPAF's with gray scale and binary input scenes. This work included experimental verification of the binary-input cases and was reported at the SPIE meeting in Orlando, Florida, in April 1992. A preprint of this paper is incorporated as Attachment B. The correlation results with binary images were at least equal in quality to those using gray scale inputs.

1.4 Some correlation filters are generated as a field of 128x128 filter values on a zero-filled 256x256-pixel array. These filters are intended for correlation with 128x128-pixel input scenes (which are imbedded in a zero-filled 256x256 array for digital simulations). Methods for implementing these filters in a correlator with 128x128-pixel SLM's at both input and filter planes (e.g., our experimental magneto-optic correlator) were investigated by both simulation and experimentation. In initial results, two methods were found to provide reasonably acceptable results:

(a) Average-down the input scene by 2X before binarizing and use the non-zero portion of the 128x128 filter array as the filter.

(b) Use the 128x128 window of non-zero input pixels as the input frame and down-sample the filter from 256x256 to 128x128 pixels.

In the remainder of this report the above activities are discussed in the order listed, and a final section will provide conclusions and recommendations for further study.

2.0 CORRELATION STUDIES USING GRAY-SCALE M-48 TRAINING SET

A set of government-furnished 256x256-pixel digital images of a model M-48 tank spanning 360 degrees of azimuth at one degree intervals was received on digital tape. The tank length filled most of the input frame and the tank image was imbedded in a field of zeroes. A training set was prepared by averaging the images down 2X to 128x128 pixels, replacing each pixel value by its square root (to simulate use of amplitude as the processor working variable), and de-meaning (i.e., subtracting the mean value of the tank image pixels). Correlation simulations and filter generation were performed using 256x256-pixel arrays. Thus input arrays were comprised of the 128x128-pixel images generated as above and imbedded in zero-filled 256x256 arrays.

Smart IMS TPAF's were formulated based on this training set. The details of the IMS filter algorithm have been reported elsewhere and may be found in Appendix A. of Attachment A. [1]. To summarize briefly, the TPAF is decomposed as a product of a BPOF (binary phase-only filter) pattern and a binary amplitude mask (BAM) that comprises a support region for the BPOF. A composite image is formed of a weighted sum of training set images representing the distortion range to be handled by the filter, and serves as the basis for forming the BPOF pattern, taking into account the effects of threshold line angle (TLA,[1]) and centering, which are basic BPOF design elements. The BAM is formulated by the sort algorithm reported by Kumar [2] to optimize SNR (i.e., discrimination) or to optimize mixed metrics (e.g., a composite of SNR and peak intensity or Horner efficiency) as explained in Appendix A. of Attachment A. For the cases at hand, a pure SNR optimization was used.

Two types of filters were formed, distinguished by the overall bandpass imposed. Filter type 'A' used the full Nyquist bandwidth of the simulations, i.e, with 256x256 pixel bandpass in the Filter array. Filter type 'B' was restricted to half-Nyquist bandwidth, i.e., with 128x128-pixel bandpass in the Filter array (which was zero-filled to 256x256 pixels). Filter type B was chosen to match a format previously used by Kallman [3] and thus also included an 11x11 pixel DC block (zero-valued pixels centered on the DC element of the filter).

For each filter type, design goals of distortion invariant performance over 37, 61, and 91 degrees of azimuth variation were addressed. These ranges were centered on a broadside view of the tank (90 degree azimuth). Filter performance was assessed in terms of signal-to-clutter ratio (SCR) as defined by Kallman [3], which is the ratio of the minimum properly located target response intensity over the design training set to the maximum false target response intensity over the entire output plane. For these studies the false target was the "basic false target" (BFT) defined by Kallman [3], which is a 128x128-pixel square of constant pixel values in a 256x256-pixel field of zeroes. Zero-mean additive Gaussian random noise is an implied additional false target of the IMS algorithm. The out-of-class power spectrum that is a basic input to the IMS algorithm was comprised of the sum of the power spectrum of the BFT plus a constant spectral density term representing white noise. The quantity that is sorted in the IMS algorithm has the out-of-class power spectral density as its denominator. The BFT (essentially a two-dimensional Rect function) has a discrete power spectrum which is zero at approximately 3/4 of its pixels (frequencies). Thus it is necessary to add a small white noise term to the out-of-class spectrum for practical numerical reasons. Viewed intuitively, the BAM could be set to zero at the approximately 1/4 of filter pixels that correspond to non-zero BFT spectrum values and the resulting filter could achieve infinite SNR with regard to the BFT noise. This is an unrealistic filter however, because a practical filter should have some rejection of stochastic signals such as white noise.

Thus the inclusion of a white noise component in the out-of-class spectrum for the IMS designs provided a practical solution to both the numerical and noise immunity issues.

Table 2.1 gives a summary of the SCR performance of the two types of filter for various training set sizes.

Table 2.1 Performance of IMS TPAFs formulated with de-meaned gray scale M-48 tank images.

Filter Type	Distortion Range (degrees)	SCR
A	37	17.76
B	37	9.21
A	61	10.61
B	61	6.06
A	91	6.63
B	91	4.03

The full-Nyquist filters provide generally superior SCR values but this must be balanced against their use of four times as many filter elements. In all cases the non-zero BAM elements closely corresponded to the elements within the applicable filter bandpass that were zero in the spectrum of the BFT. Thus approximately 75% of the filter elements in the respective bandpasses were set to the BPOF values (-1 or 1).

Some of the filters reported above were tested with inputs including additive Gaussian noise with a standard deviation of 25 units. For each training set image used, ten input variants were formed using different random noise samples and results were averaged over the resulting set. Table 2.2 provides the results of this study.

Table 2.2 Results of simulated correlations of gray-scale M-48 tanks with added noise.

Filter Type	Training Set Size	Input Azimuth (degrees)	Average SCR
A	91	50	3.91
A	91	90	3.02
B	61	90	4.36
B	61	115	5.48
B	91	90	3.70
B	91	115	5.25

These results indicate significant but not excessive degradation of SCR (relative to the BFT) in the presence of additive input noise.

3.0 CORRELATION PERFORMANCE WITH BINARY IMAGES

A study to assess the performance of basic BPOF correlationwith binary images is reported in detail in Attachment A., which is a report entitled "A Study of Image Binarization for Optical Correlation," by David L. Flannery and Scott D.Lindell (of Martin Marietta), dated 22 August 1991.

4.0 COMPARISON OF BINARY AND GRAY-SCALE CORRELATIONS WITH SMART FILTERS

Using a second set of government-furnished images with a T-72 tank target, IMS TPAFs were formulated to handle ranges of azimuth and scale distortions for both gray-scale and binary versions of the same images. The correlation performance was assessed in simulations and selected binary cases were verified in our experimental correlator. This phase of the effort is reported in detail in Attachment B which is a preprint of a paper delivered at the April 1992 SPIE meeting in Orlando, Florida [4].

5.0 TECHNIQUES FOR EXPERIMENTAL IMPLEMENTATION OF HALF-NYQUIST FILTERS.

As noted in the Introduction (Section 1.0), some researchers prefer to define filters as 128x128 active pixels on a field of 256x256 zeroes, comprising a filter with imposed half-Nyquist bandpass. These filters are used in digital simulations in which the input scene is also 128x128 pixels on a zero-filled 256x256 format. The motivation for the zero-filled formats is to preserve adequate sampling of the discrete Fourier spectrum and the zero-filling technique is well known. The need for zero filling in the filter domain is arguable but a practical problem arises when the experimental implementation of such filters in a pixelated correlator having 128x128 pixels in both input and filter devices is contemplated. Normally the experimental correlator is configured (by choice of lens focal lengths and spacings) so the full Nyquist bandpass corresponding to input SLM pixel spacing is mapped to the full extent of the filter SLM (i.e., to 128 pixels). Thus there is no straightforward method of implementing the zero-filled inputs and filters of the digital simulation in such a correlator. Even though the filter pattern has only 128x128 information carrying elements, these elements correspond to only half the Nyquist bandpass or to a 64x64 pixel area of the filter SLM. In summary there is a transform scaling discrepancy that must be dealt with before experimental implementation is possible. Several approaches to this problem were considered and the results are provided here.

5.1 Approaches

To achieve scale matching of the optical transform and the filter pattern starting with the fundamental 2:1 mismatch described above, two basic approaches suggest themselves:

a. Scale down the input pattern by 2X in the input SLM. This scales the optical transform up by 2X and allows the 128x128 active (half-Nyquist) portion of the filter pattern to be directly mapped into the filter SLM.

b. Scale down the filter pattern by 2X so that 256x256 pixels are mapped into the available 128x128 SLM pixels, thus preserving full Nyquist bandpass mapping of the filter format.

Further discussion is needed to illustrate the non-ideal aspects of either approach and to delineate detailed options within each basic approach.

Scaling down the input pattern has the attractive advantage that twice the input scene size originally used in the digital simulations can be input to the correlator. The scale-down implies a loss of high spatial frequencies but this effect corresponds exactly to the half-Nyquist bandpass originally built into the filter and thus represents no additional loss of information. For gray-scale images, a simple 2X average down process would seem most appropriate. For binary inputs (applicable to our correlator) the situation is more complicated. The final input image must be binary and this can be achieved by two routes:

a. Average down the full-scale gray scale image (if available) by 2X and then binarize.

b. Down-sample the full scale binary image by 2X.

It should be apparent that due to the intrinsic non-linearity of forming a binary image these two procedures are not equivalent and neither can be shown to be equivalent to a simple low-pass filtering operation applied to the full scale binary image (as can be shown for the average-down procedure applied to gray-scale images). Both these methods were investigated initially but as suspected the down-sampled input method was unacceptable because of large fluctuations of results depending on how the sampling grid aligned with a particular binary image for realistic cases where single-pixel wide image lines existed. Thus only the averaged-down input technique received serious attention.

The same two basic approaches exist for scaling down the filter pattern with the slight difference that the result must be forced to ternary phase-amplitude values (-1,0,1). Down-sampling by 2X is straightforward. Averaging down 2X is numerically complicated by two factors. First, the averaging down process must be kept symmetric about the DC (zero spatial frequency) filter element, which requires a 3x3 kernel convolution rather than a simple 2x2 cell average, and second, there is no established thresholding technique for partitioning averaged pixel values into the three filter modulation levels (whereas input scenes are binarized with a predetermined algorithm). Initial simulations using the latter procedure yielded very poor results. Thus only the down-sampled filter approach was given serious attention.

The above approaches and their variants define two specific methods of handling the half-Nyquist filter implementation, both of which were studied in simulations.

5.1 Simulation Results

A representative sampling of the correlation simulations performed are presented in table 5.1 . These results are for the binary T-72 images used in the work reported in Section 4. and are for the case of a distortion range of 5x13 (5 1.5% scale steps and 13 degrees of azimuth). In the table, peak intensity is given in units that correspond to the intensity of a single binary pixel at maximum intensity and "P/C" denotes peak-to-clutter which is the ratio of valid correlation peak intensity to the next highest peak in the output.

Table 5.1 Correlation simulation results indicating relative performance of methods for implementing half-Nyquist filters.

Input	Filter	Peak intensity (units)	P/C (dB)
256	256	1.56	5.1
Averaged	Windowed	1.93	5.2
Windowed	Sampled	1.78	5.2

The tabulated results indicate that there are small differencesbetween the various methods and that the most accurate simulation (using full 256x256 arrays for both input and filter, corresponding to the first data line in the table) actually produced a slightly lower peak intensity. The exact values shown should not be taken too seriously since they apply to one particular case and the relative performance varies from case to case by perhaps 30% in peak intensity and one dB in P/C. There is also an apples-vs-oranges aspect to the tabulated results in that a higher binarization threshold (resulting in fewer 'on' pixels) was used for forming the input image in the case of averaged-down input in order to achieve comparable correlation results. Without this adjustment this method would yield a higher peak intensity (1.99 units) but only 2.2 dB P/C.

The method defined by windowing the 128x128 active area of the input scene and down-sampling the filter yielded results comparable to the full-resolution simulations across many cases tried in addition to the one shown in the table. In view of this and the fact that the other method requires an ad hoc adjustment of the binarization threshold to achieve comparable results, the former is judged the most acceptable method for implementing a half-Nyquist filter design on full-Nyquist magneto-optic correlator. The other method has the advantage of allowing four times as much input scene to be handled in one correlation if the need to adjust binarization threshold is acceptable.

5.2 Experimental Verification

Figures 5.1 and 5.2 provide simulation and experimental correlation intensity plots for cases representing each of the two methods. The case shown in Figure 5.1 had a P/C value of 5.4 dB in simulation and 3.1 dB experimentally. The case shown in Figure 5.2 had 5.4 dB in simulation and 2.5 dB experimentally.

These discrepancies between experiment and simulation are not unusual because the peak intensity (from simulations) of these correlations is at the very low range of values (2 to 2.5 units) that we know empirically can be successfully implemented in this correlator. The existence of this lower limit is presumed due to a noise floor in the correlator that is not represented in the simulations.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions.

The results of this effort support the following conclusions:

6.1.1 Smart TPAF's provided correlation performance comparable to smart POF's and BPOF's formulated via other algorithms for the case of a de-meaned gray scale target with the BFT (basic false target) defined as the out-of-class pattern.

6.1.2 Correlation performance of simple BPOF filters on binary M-48 tank images was shown to be excellent in both simulations and experimental implementations.

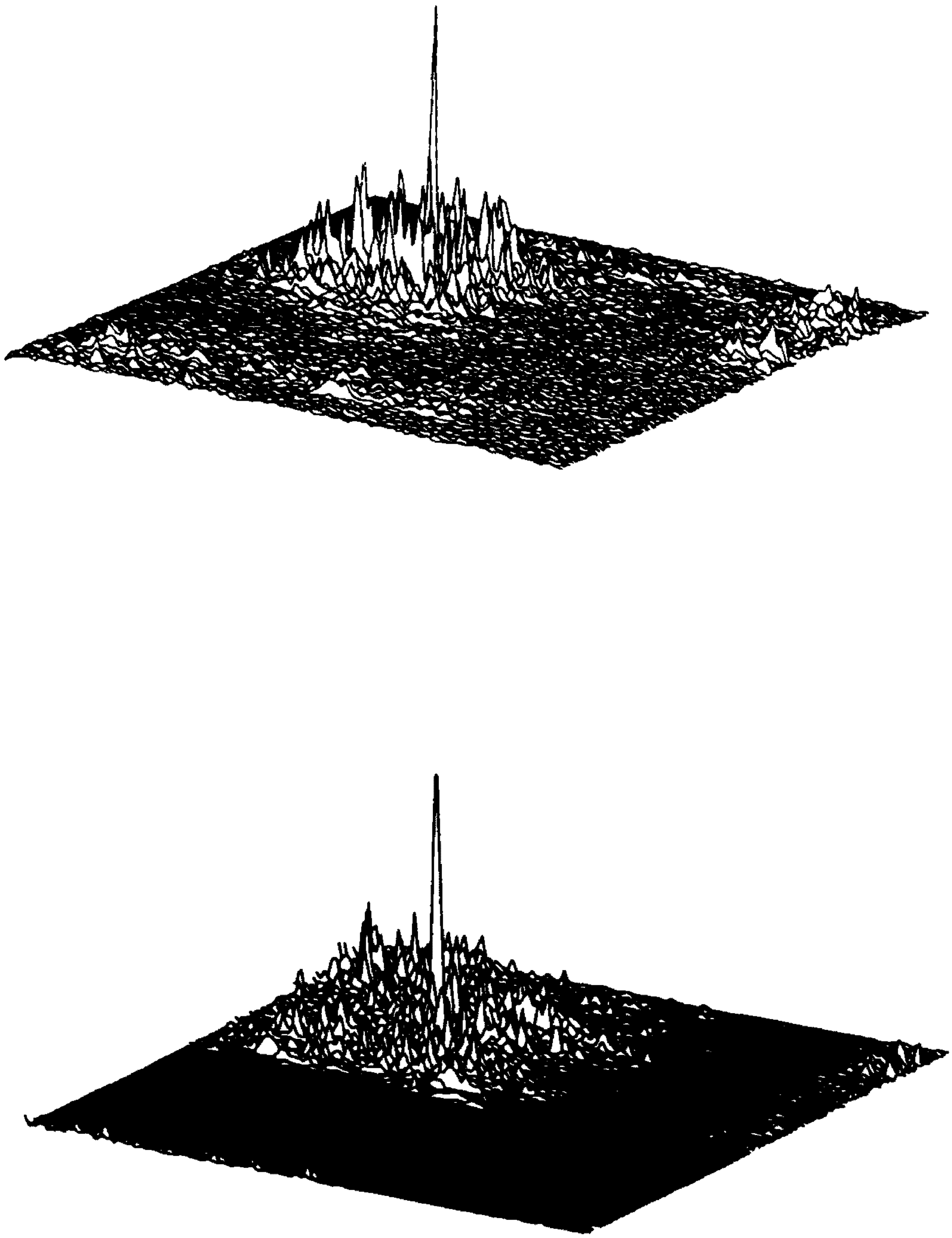

Figure 5.1 Simulation (top) and experimental correlation intensity plots for 5x13 half-Nyquist T-72 filter with input scene averaged down prior to binarization and windowed filter pattern.

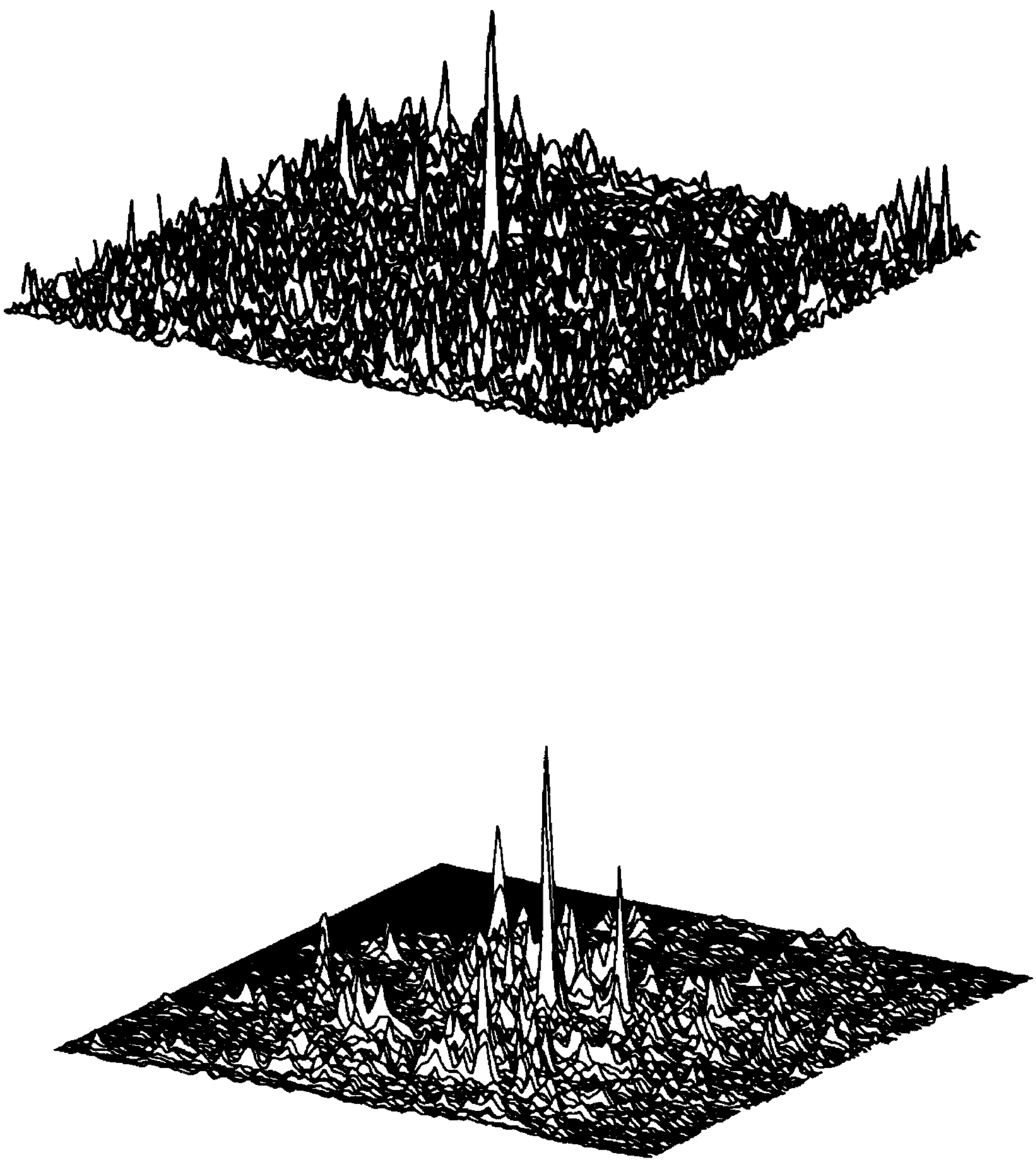

Figure 5.2 Simulation (top) and experimental correlation intensity plots for 5x13 half-Nyquist T-72 filter with input windowed and filter down-sampled.

6.1.3 Smart TPAF's exhibited useful azimuth and scale invariant correlation for realistic scenes involving a tank on a clutter background, although some scenes overwhelmed the filter when the clutter was located too close to the target. This performance was shown for both gray-scale and binary versions of the same scenes using filters formulated for the respective cases. Binary scene correlation performance was at least as good as gray-scale performance, arguably better.

6.1.4 Initial simulations and experimental verification indicate that half-Nyquist bandpass filters designed on a 256x256 pixel format can be evaluated in a 128x128 pixel full-Nyquist experimental correlator by using a 128x128 input window and down-sampling the filter pattern by 2X. An alternate scheme involving averaging down the input by 2X prior to binarizing and using the half-Nyquist window of filter values also showed promise but may involve modification of the input binarization scheme to achieve results comparable to ideal 256x256 simulations.

6.2 Recommendations

6.2.1 It is recommended that work continue on the development of smart TPAF formulations and their application to realistic target-on-background images, including the use of binary images for ready implementation on available spatial light modulators.

6.2.2 It is recommended that TPAFs developed by other researchers for binary input scenes be verified experimentally on our magneto-optic correlator. This may involve the application of the methods developed in this work to implement half-Nyquist 256x256-pixel filters on a 128x128-pixel format.

6.2.3 It is recommended that additional study be conducted to verify the initial favorable results obtained in this study on methods for experimentally implementing half-Nyquist 256x256 filters.

7.0 REFERENCES

1. D.L. Flannery and S.D. Lindell, "A Study of Image Binarization for Optical Correlation," Technical Report, Martin Marietta and University of Dayton Research Institute, 22 August 1991.

2. B. Kumar and R. Juday, "Design of Phase-only, Binary Phase-only, and Complex Ternary Matched Filters with Increased Signal-to-noise Ratios for Colored Noise," Optics Letters, Vol. 16, pp. 1025-1027, 1 July 1991.

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4. D. Flannery, W. Phillips, R. Reel and D. Goldstein, "Comparison of Correlation Performance of Smart Ternary Phase-amplitude Filters with Gray Scale and Binary Input Scenes," Proc. SPIE Vol. 1701 (in press), Orlando, FL, April 1992.

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